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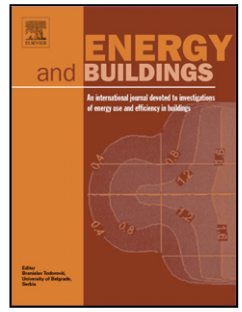


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# Detailed and simplified window model and opening effects on optimal window size and heating need

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**Highlights**

- Detailed triple window modelling increased predicted heating needs by up to 7%.
- Detailed triple window modelling decreased predicted cooling needs by up to 23%.
- Detailed and simplified quadruple window models resulted in similar energy needs.
- Window models and opening strategies caused 20% variations in optimal window sizes.
- Multiplying the simplified triple glazing U-value by 1.15 was suggested in Estonia.

**Abstract**

The purpose of this study is to quantify the gap between the calculated energy need of a building model with simplified and detailed windows and suggest a method for reducing the gap. A model of a detached house in the cold climate of Estonia was composed and its energy needs with triple and quadruple windows was studied. The window sizes and opening strategies were also varied and all cases were modelled with simplified and detailed window models of which the latter were modelled pane by pane according to the methodology of ISO 15009. Simplified window models resulted in heating need lower by up to 7% and cooling need higher by up to 23%. The optimal window sizes of South facing triple windows remarkably depended on the glazing model and window opening strategy used. Therefore using simplified window models and inappropriate methodology might lead to inadequate facade design. In case of triple windows multiplying the U-value of simplified window models by 1.15 minimized the mismatch in calculated heating needs with different window models. It is recommended to use detailed window models to be used in simulations of mechanically cooled buildings.

**Keywords:** Energy simulations, windows, glazing, façade design, energy efficiency, indoor climate

## 1 Introduction

Several countries in the European Union require making energy simulations to prove new buildings' compliance with energy performance minimum requirements. Expected energy use is calculated, however it rarely complies with actual measured consumption. Reducing the gap between calculated and measured energy is currently one of the main problems faced in the field of building energy analyses.

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Façades have a large effect on the building energy use while the size and properties of glazed areas are especially important. Numerous papers on optimizing window areas have been published. Thalfeldt et al. [1] and Pikas et al. [2] studied cold climate office building facades with several glazing types and optimized the total cost of investment and energy over a 20 year period. It was concluded that triple windows with areas that assure the required daylight factor 2% is the financially feasible solution and in case of four and five pane windows, larger window areas could be used to optimize energy use. In the study published in 2011, Jaber and Ajib [3] studied various window types and sizes in three different climates with Berlin being the coldest. They concluded that window design, especially glazing choices, is a critical factor to effectively utilize solar energy. At that time, double glazed windows were the most economically reasonable choice and triple windows showed best performance regarding energy use. Persson et al. [4] studied the window sizes of dwellings in a cold climate and pointed out that the window size of South-oriented windows does not have a remarkable effect on heating need and smaller windows might be reasonable to reduce over-heating and cooling needs. Gasparella et al. [5] analyzed the energy performance of a single-family house in four different European climates with varying window types and sizes. They pointed out that large glazed areas with low thermal and high solar transmittance improve winter performance and worsen summer performance. The latter could be improved by installing selective shading systems. On the other hand, Ihm et al. [6] suggested imposing an upper threhold level for the solar heat gain coefficient for windows of residential buildings after modelling a building in two major South-Korean climate zones. Vanhoutteghem et al. [7] studied various facade window parameters' effect on energy use, thermal indoor environment and daylighting in Danish nearly zero-energy single-family houses. They concluded that in well-insulated houses increasing g-values above 0.3-0.4 has a limited effect on reducing heating demand and U-values between 0.3-0.5 W/(m$^2$ K) are needed for using large glazed areas. They said that windows have to be carefully dimensioned to reach the daylight target without overheating South-oriented rooms. Similar suggestions were given by Skarning et al. [8] for the climate of Denmark and they added that slighly higher U-values could be used in the climate of Rome. Skarning et al. [8] also pointed out that focus should be set on minimizing thermal transmittance of glazing and frames instead of maximizing solar gains in South-oriented rooms, which increases the risk of overheating. Opening windows is an effective method to reduce overheating according to Mavrogianni et al. [9] and Rijal et al. [10]. Rijal et al. concluded that people open windows, when indoor and outdoor temperatures increase and they developed an adaptive algorithm for window-opening behaviour.

All the previously mentioned articles used energy simulations and it essential to determine that the used software is validated. Roux et al. [11] developed a glazed space simulation model and succesfully validated it. A dynamic energy and indoor climate modeling tool IDA-ICE [12] was used in the current analysis and several studies have also included this software. Bring et al. [13] have described the mathematical models used in IDA-ICE in Neutral Model Format that can be automatically translated into executable code for various simulation environments. In 2003-2007 Loutzenhiser et al. [14] validated several dynamic energy and indoor climate simulation tools and made suggestions for improving the softwares. IDA-ICE 4.0 was among the studied programs and it performed well in comparison with other

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softwares. Validation processes of IDA-ICE have been described in Ref. [15] and [16]. The detailed window model of IDA-ICE has been validated against ISO 15099 [17] and a modelling software Window [18], which is developed by Lawrence Berkley National Laboratory. Crawley et al. [19] compared 20 energy simulation softwares and the study indicated that IDA-ICE is suitable for analysis of glazed areas. Hilliaho et al. [20] measured air temperatures in glazed and unglazed balconies and compared them with simulated ones, which were obtained by using IDA-ICE 4.6. The correlation was good and highest modelling accuracy was reached by using detailed window and zone climate models.

Generally, energy specialists use simplified window models with constant U-values in energy simulations, however the thermal resistance of glazing varies depending on the outdoor temperature, wind speed and direction. Kurnitski et al. [21] showed in their article that the temperature difference between inside and outdoor conditions affects the thermal transmittance of glazing significantly. Petersen [22] calculated the heating energy of a building using a constant declared U-value of glazing and a more accurate dynamic U-value that varied for each hour of the climate year. Constant U-value could lead to significant under estimation of heating energy in cold climates and Petersen suggested using the described dynamic method for energy calculations. Several dynamic simulation softwares including IDA-ICE 4.6 [12] allow creating detailed glazing models consisting of panes, cavities and shading devices. Detailed window models take the changes in external conditions into account and calculate the energy balance of glazing more accurately than simple models. In Ref. [23] energy simulations were conducted to determine the differences in calculated energy use of a detached house in Estonia if simplified and detailed window models were used and concluded that gaps in heating and cooling needs were up to 7% and 23% respectively. The use of detailed glazing models was recommended, but also a correction factor of 1.15 was suggested for simplified triple glazing model, when calculating only the heating energy.

The purpose of this study is to quantify the gap between the calculated energy need of a building model with simplified and detailed windows and to suggest a method for reducing the gap. A model of a detached house in the cold climate of Tallinn, Estonia was composed and its energy needs with triple and quadruple windows were studied. The size of glazed area in the South and West façades was also varied. Cases with closed windows were compared to a model where windows were opened to reduce over-heating and a case with cooling was added. The difference in energy needs between models with simplified and detailed windows were compared, correction factors for simplified window U-values to reduce the gap in heating need were calculated and tested. Optimal window sizes with various glazing models and opening strategies were calculated and also over-heating degree hours during the summer period were investigated. In comparison to Ref. [23] the current article presents the results of West facade analysis and additional information regarding solar gain differences between models and studied summer-time over-heating was added.

## 2 Methods

The analysis was conducted in the following steps:

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1. Simulations with a simple 2.5x4.0 m South facing zone model to determine the heat losses at design outdoor temperature and to verify the annual solar gains through different glazing models with number of panes ranging between 2 and 5
2. Energy and indoor environment simulations of a model of a detached house (Figure 1) with triple and quadruple glazing, varying window sizes, simplified and detailed window models
3. Comparing the heating and cooling needs of models, that had simplified and detailed window models and were identical otherwise. Determining the gap between the energy needs of models with simplified and detailed windows
4. Determinining the window sizes that result in smallest heating and cooling needs, which were considered the optimal solution
5. Determining the correction factor for simplified triple glazing models and verifying the remaining mismatch in energy need calculations

## 2.1 Calculation principles of different glazing models

The used modelling software IDA-ICE offers the opportunity to use either simplified or detailed window models. The simplified window models are called Standard windows and their parameters are constant throughout the simulations, while the energy balance of detailed windows are modelled according to physical formulas. Simplified window model is based on common properties of the glazing unit, which are solar and visible transmittance, U-value and internal and external emissivity. Due to different calculation methodologies, the simulation results also vary and the main reasons for that are described in the following paragraphs.

The glazing properties in product sheets are generally given at standard conditions according to ISO 15099 [17] i.e. at temperature difference of 20 °C. When room temperature is 21 °C, then in static conditions the declared U-value corresponds to the actual one if outdoor temperature is 1 °C. In case of lower temperatures, the glazing thermal transmittance is higher. The outdoor temperatures are below 1 °C for most of the heating period in a cold climate of Estonia, which is described by the test reference year [24] (Figure 2). Therefore the thermal transmittance of windows during the heating period is generally larger than in standard conditions.

Another important difference is that simplified glazing models use an angle dependence to calculate the solar transmittance and absorptance of glazing, while the energy balance of detailed window models is calculated based on physical formulas. Each pane and their interactions of detailed glazing are taken into account with detailed window models as shown in Figure 3. The figure also describes the simplified window model. Detailed window model calculation principle has been composed according to the methodology of ISO 15099 [17], which however does not cover the calculation of single pane angular properties. The implemented methodology for calculating the angular properties has been documented in ASHRAE Fundamentals [25]. The input parameters of the windows used in the simulations of this study have been described Section 2.3.

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## 2.2 Detached house simulation model

Energy simulations were conducted on the basis of a simulation model of a two-storey detached house with total heated area of 144.2 $m^2$. The building has large windows in South and West orientations and the North façade has small windows. The plans and 3D view of the model are shown in Figure 1. The building is constructed of light-weight timber frame walls, floors and roof. Table 1describes the areas and thermal conductivities of the building envelope elements. Each of the 10 rooms was modelled as a separate zone, because summer-time over heating was analyzed besides energy needs. The over-heating degree hours of the room with highest risk were calculated to assess the buildings compliance with the over-heating requirements.The Estonian methodology for calculating the energy performance of buildings described in Ref. [9] was used. Well-validated simulation software IDA-ICE 4.6 [12] and Estonian reference year [24] and the location of Tallinn were used for performing energy simulations. Mechanical supply and exhaust ventilation with heat recovery was used. The usage factor of occupants and equipment was 60%, 10% for lighting and ventilation worked at all times. The initial data of simulation model is shown in Table 2.

## 2.3 Window types

Highly transparent triple and quadruple glazing that had two and three low emissivity panes respectively were analyzed. Figure  displays the analyzed glazings and the positioning of low-emissivity coatings. In IDA-ICE detailed window models as is described in Table 3 were created with pane properties shown in Table 4. The average frame ratio of the studied window sizes was 20% and it was assumed as a constant for all cases to simplify the calculations. The window properties shown in Table 4 were used as constant values in simplified window models.

## 2.4 Simulated cases

The simplified and detailed windows were compared using all combinations of the following variables:

1. Triple or quadruple glazing
2. Window width in the South facade 1.8, 2.0, …, 4.6 meters
3. Window width in the West facade 1.5, 1.7, ..., 3.9 meters
4. First floor window height 2.2, 2.3, 2.4 or 2.5 meters, second floor windows were 0.1 meters lower in each case
5. Window opening and cooling:
    a. Windows were closed at all times, no cooling or
    b. From 6 p.m. to 6 a.m. windows were opened 20% if room temperature exceeded 27 °C and the outdoor temperature was lower than indoor temperature, no cooling or
    c. From 6 p.m. to 6 a.m. windows were opened 20% if room temperature exceeded 25 °C and the outdoor temperature was lower than indoor temperature, the cooling system setpoint was at 27 °C.

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Initially, the width of the South facing windows was 2.4 meters and the height of the windows was 2.4 and 2.3 meters in the first and second floors respectively. The initial width of the West facing windows was 1.5 meters and the height of the windows was 2.3 and 2.2 meters in the first and second floors respectively. When the WWR of windows in either South or West facade was analyzed, then the initial window size was used in the other facade.

## 2.5 Predicting the correction factor for the U-value of simplified window model

The simulations with simplified and detailed window models result in different heating energy needs. Acquiring detailed information about window panes from the manufacturers can be currently difficult and time consuming for energy efficiency specialists. Therefore, it was tested if using a correction factor for the U-value of simplified window models could minimize the error in simulation results. It was attempted to predict the correction factor based on the proportion of glazing in the total heat losses of the building taking into account the window sizes and the relationship between simulated heating needs with detailed and simplified window models. Finally, the predicted correction factor was calculated based on the relative difference of modelled heating needs and the proportion of glazing heat losses. The methodology was then tested, if it can be used to predict the correction factors.

The proportion of glazing in the building heat losses was calculated according to formula 1 using values from Table 1.

$$\frac{H_{GL}}{H_{TOT}} = \frac{H_{GL}}{H_{WIN} + H_{EW} + H_{other}} = \frac{(1 - F_f) \cdot A_{WIN} \cdot U_{GL}}{A_{WIN} \cdot U_{WIN} + A_{EW} \cdot U_{EW} + H_{other}} \quad (1)$$

Where,

| | |
|---|---|
| $H_{GL}$ | specific heat loss of glazing, W/K |
| $H_{TOT}$ | total specific heat loss of the building, W/K |
| $H_{WIN}$ | specific heat loss of windows including both glazing and frames, W/K |
| $H_{EW}$ | specific heat loss of external walls, W/K |
| $H_{other}$ | specific heat loss of slab on ground, roof, doors, thermal bridges, infiltration and any other components of heat loss W/K |
| $F_f$ | frame fraction of total window area, - |
| $A_{WIN}$ | area of windows, m$^2$ |
| $U_{GL}$ | glazing U-value at standard conditions, W/(m$^2$K) |
| $U_{WIN}$ | window U-value at standard conditions, W/(m$^2$K) |
| $A_{EW}$ | external window area without windows, m$^2$ |
| $U_{EW}$ | external wall U-value, W/(m$^2$K) |

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The correction factor for simplified window glazing U-value could be used to minimize the gap in simulated energy needs. It was predicted for each case with formula 2:

$$f_{corr} = \left( \frac{Q_{DET}}{Q_{STDR}} - 1 \right) \Big/ \frac{H_{GL}}{H_{TOT}} + 1 \qquad (2)$$

Where,

$f_{corr}$ correction factor, -

$Q_{DET}$ heating energy in case of detailed windows, kWh

$Q_{STDR}$ heating energy in case of simplified windows, kWh

$H_{GL}$ specific heat loss of glazing, W/K

$H_{TOT}$ total specific heat loss of the building, W/K

The calculated correction factors varied (see section 3.4) and therefore all simplified window cases with glazing U-value correction factors 1.1, 1.15, 1.2 and 1.25 were simulated. The correction factor resulting in the smallest difference between the heating energy of detailed and simplified window models was suggested for using in energy calculations with simple window models.

# 3 Results

## 3.1 Glazing U-values and heat losses

Simple simulations with IDA-ICE according to ISO 15099 [17] show that glazing U-value depended on indoor and outdoor air temperature difference. Figure  illustrates the detailed glazing model U-value in case of different outdoor temperatures and number of panes. The glazing U-value increased when it was colder outside and it only equaled the declared value at outdoor temperature 1 °C i.e. with 20 °C temperature difference. Figure  shows that at the Tallinn design outdoor temperature -22 °C heat losses per heated area m$^2$ with simplified glazing were smaller by up to 3.5 W/m$^2$ i.e. 11.1% with triple glazing. Quadruple window cases had heat loss with simplified glazing was smaller by up to 1.2 W/m$^2$ i.e. 4.4%.

## 3.2 Direct solar radiation through glazing

Simulations with simple models in IDA-ICE showed that simplified glazing allowed more direct solar radiation into the zone than detailed models (Figure ). Throughout the year the total amount of direct solar radiation differed by 10-14 kWh/m$^2$ of glazing area, which corresponded to relative difference of 5.5%, 11.1%, 18.1% and 26.4% in case of 2 to 5 pane glazing respectively.

## 3.3 Energy needs

The comparison of glazing models show that in case of triple glazing simplified window models resulted in lower building heating need by 1.4-2.6 kWh/m$^2$ of heated area when South facade windows were changed (Figure ). The difference was between 1.6-2.5 kWh/m$^2$ when

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West facing window areas were changed (Figure ). In case of quadruple windows the heating need with simplified windows could be lower by up to 0.2 kWh/m$^2$ or higher by up to 0.1 kWh/m$^2$ compared to detailed window models and the differences were similar when either South or West facade window sizes were varied. The gaps in the energy needs with different glazing models were higher in case of larger window areas and when there was no window opening and cooling. The window-to-wall ratio (WWR) resulting in lowest heating need did not depend on the window model used in case of changing West facing window sizes or quadruple glazing, however with triple windows oriented to the South the optimal window area differed depending on the glazing model used.

The simulations with detailed triple windows resulted in lower window-to-wall areas that assured minimum heating need than standard windows. Also window opening and adding a cooling system lowered the respective window size. The WWR of South facing triple windows with minimum heating needs was between 39% and 76%. The lowest heating need was achieved with the smallest West facade windows. In case of quadruple windows the gap between optimal window sizes was smaller and minimum heating need was achieved with WWR between 76% and 86% on South facade. In cases without cooling, the WWR assuring minimum heating need was considered as the optimal one considering only energy use, however the summer-time overheating anaylsis had to be performed before the solution could be suggested.

The cooling need was higher with standard windows in all cases with differences between 1.1 and 3.6 kWh/m$^2$ in case of triple windows and 0.5 to 2.0 kWh/m$^2$ in case of quadruple windows when the South facade window-to-wall ratio was changed (Figure ). The differences increased with larger windows. Generally, the absolute differences between the window models was higher in case of cooling then heating. Therefore, in case of buildings with cooling the total energy need was reached with standard window models (Figure ). The cooling energy need analysis results with varying window sizes in the West facade were similar to the ones depicted in Figure  and Figure . As the cases with cooling had lowest energy needs, then it could be stated that smaller windows improve energy-efficiency if cooling is used.

### 3.4 Correction factors

The standard window U-value correction factors for minimizing the gap in energy need with detailed window models were calculated based on the proportion of glazing in total heat losses of the detached house and the difference in the heating needs of models with standard and detailed windows. The correction factor ranged between 1.17 and 1.25 depending on the case and the factors were highest in case of closed windows and lowest if window opening was allowed and a cooling system was used (Figure ). Based on calculated correction factors and adjustments during the work and the following corrections factors to standard triple glazing U-values – 1.1, 1.15, 1.2 and 1.25 were experimented with.

### 3.5 Minimizing the gap in energy need

The heating need without any correction in the glazing U-values was with simplified glazing models 3.7% to 7.0% lower than with detailed glazing models if the size of South facing

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windows was changed (Figure  part a). The difference was between 4.9% and 6.1% when only the size of West facade windows varied (Figure  part f). In both cases the gap in heating needs with different glazing models increased with larger windows (Figure ). Also the differences in heating energy were slightly larger with no window opening and cooling compared to alternatives. The gaps in cooling need were from 21.1% to 23.5% with simplified windows resulting in higher cooling energy use, whereas there was no remarkable difference whether the South or West facing windows were changed (Figure  parts d and i). The total energy need of heating and cooling was smaller by up to 0.7% with small simplified windows and larger by up to 2.8% with large simplified windows if the size of South facade windows was changed (Figure  part e). When the West facing windows were changed then total energy need was larger by up 0.8% with simplified glazing models (Figure  part j).

The comparison of simulated energy needs of the building model with simplified and detailed windows shows that using correction factors could reduce the difference remarkably in case of building with only heating. Multiplying simplified window U-value with correction factor 1.15 resulted in lowest difference in heating energy, which was different than the predicted correction factor of 1.2 calculated with formula 2. Therefore the formula could not be used for predicting the correction factors. In closed window cases, the differences in heating need remained within 0.1% (Figure  part a) and 0.5% (Figure  part f) when South or West facing windows were changed respectively. When windows were opened to reduce over-heating, then correction factor 1.15 resulted in 0.2-0.8% higher (Figure  part b) and 0.3-0.9% higher (Figure  part g) heating need in case of simplified glazing. The differences in the heating need were highest in case of building models with cooling correction factor 1.15 (Figure  parts c and h), however cooling energy should also be observed. Increasing the U-value of simplified window models decreased the gap in cooling energy, however the difference remained above 16% in all cases (Figure  parts d and i). As mentioned before, the difference in cooling energy is generally higher than in heating energy, if simplified and detailed glazing models are compared. Therefore the correction factors did not decrease the difference in total energy need in case of buildings with cooling (Figure  parts e and j). Simplified glazing U-value correction factors could only be used in case of building without cooling and the correction factor 1.15 should be used for triple glazing with U-value 0.55 W/(m$^2$K) in a cold climate typical to Estonia.

### 3.6 Summertime over-heating

Besides energy use summertime over-heating was analyzed. Estonian legislation states that modelled room temperature in dwellings must not exceed 27 °C by more than 150 °Ch during the period of 01.06.-31.08 [26]. Figure  displays the results of summertime over-heating analysis of the bedroom located in the South-West corner of the second floor. Similarly to energy use, there was a difference in the results obtained with detailed and simplified triple glazing models and in case of quadruple glazing there was no large difference between window models. Triple simplified window models resulted in higher degree-hours exceeding 27 °C and the gap was 19-25 °Ch. Requirements for over-heating were exceeded with simplified triple window models, if window-to-wall ratio was above 60%, however all cases with detailed windows fulfilled the requirements.

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## 4 Discussion

Various methods are used to assess the energy use of a building during the design phase and naturally they all have different results. In general these methods fall into two large groups – simple yearly or monthly methods and more detailed dynamic modelling. In theory dynamic simulations with validated softwares are more accurate, however their results are sensitive to the large number of input parameters. The current study showed that calculated optimal size of a South facing window of a detached house varied remarkably even though only a single software was used. Sophisticated simulation softwares require experienced users, who have the ability to assess the influence and importance of input parameters to the output of the conducted analysis. As dynamic modelling of energy use and indoor climate of building is becoming more common, it is a challenge to accurately define occupant behaviours to be used in energy simulations. Our analysis showed that window opening affected the optimal window size in the South orientation and besides precise modelling tools, an effort has to be to predict the impact of occupants as realistically as possible.

It is a wide-spread rule of thumb that large glazed areas should be used in the South facade to ensure good energy efficiency, because the annual energy balance of glazed area is supposed to be positive. The results of the study indicate that in a Nordic climate following this principle might not be appropriate and large amounts of solar energy were not utilized usefully. In addition, occupants let out excess solar heat by opening windows, however traditionally that is not taken into account during energy analysis. The study also indicated that the heating need on the building did not depend much on the window size in the South orientation. Therefore various other indicators could be used in sizing of these windows such as heating or cooling capacity, over-heating degree-hours and architectural aspects. Larger window sizes in the West facade had a remarkable effect on the increase of energy use and similar principle might also apply for East and North facades, however this aspect needs more studying. Rules of thumb and experience could be used for initial building design solutions, but it is suggested to verify their suitability with dynamic modelling softwares, which depict the realistic situation as accurately as possible.

## 5 Conclusions

Energy simulation based façade analysis requires using precise input data and correct methodology to reach adequate results. An analysis of South and West facing window sizes of a detached house in Estonian climate was conducted. Simplified and detailed window models and different window opening strategies in energy modelling software IDA-ICE 4.6 were used to determine optimal window sizes and the differences in the outcome of the simulations. The study shows that in the cold climate of Estonia detailed modelling of glazing results in higher heat losses and lower cooling needs than simplified models. It was mainly caused by simplifications made in calculating the solar gain through simplified window models. The second reason was that simplified glazing models used a constant U-value, which applies in case of temperature difference of 20 °C, but detailed window models take into account increased thermal conductivity of glazing at larger temperature differences, which are dominant during the Nordic heating period. The heating energy needs differed by up to 7% with compared window models and the gap was even larger in cooling energy reaching 23%.

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Triple glazing had significant mismatch in the energy use of simplified and detailed models, while the simulated energy with quadruple glazing corresponded well.

The study results suggest increasing the U-value on simplified efficient triple glazing by a factor of 1.15 in Estonian climate. However, it must not be forgotten that different correction factors should be used with other glazing types and climates. In the building without cooling the deviation was possible to compensate, but buildings with both heating and cooling were challenging as the total energy need can be either smaller or larger when simplified and detailed models are compared. Therefore correcting only the U-value of simplified glazing cannot be used in such cases. It has to be studied further, if using additional correction factor e.g. for g-values could reduce the gap in the simulated energy. Right now it can be recommended to use detailed window models for that mechanically cooled buildings in cold climates.

In case of buildings without cooling simulating simplified glazing over estimates the optimal window size in the South facade, which in addition to inaccurate energy use also increases over-heating during summer periods. The optimal window-to-wall ratios differed by up to 10% in case of South facing triple windows, when the calculated heating needs with different window models were compared. Whereas window opening could have even larger influence on the optimal window size. Minimum South facing triple window-to-wall ratio were smaller by up to 20% when in the simulation the windows were opened by 10% to cool the building when room temperature exceeded 25 °C instead of constantly closed windows. Therefore using simplified window models might lead to inadequate façade design.

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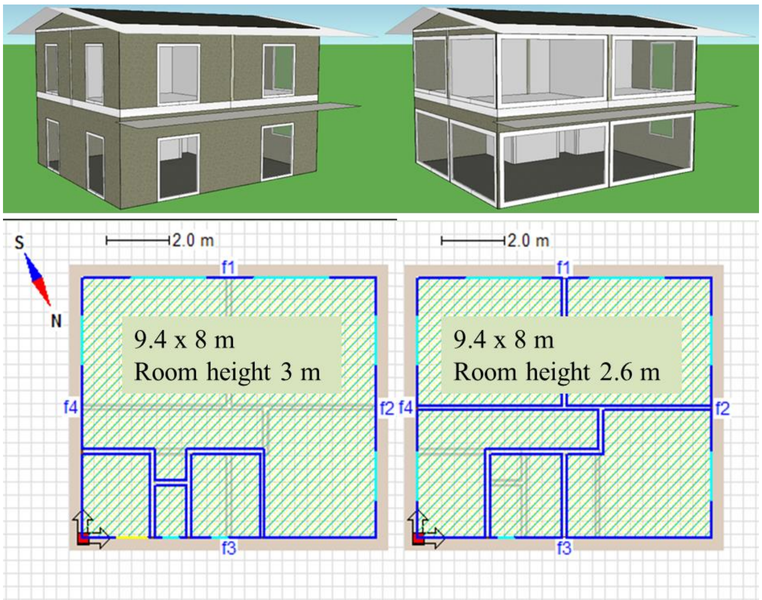


**Figure 1 The 3D view from South-West with minimum and maximum window sizes (top left and right respectively), first and second floor plans (bottom left and right respectively). The light blue lines on the perimeter of building envelope show the positioning of windows.**

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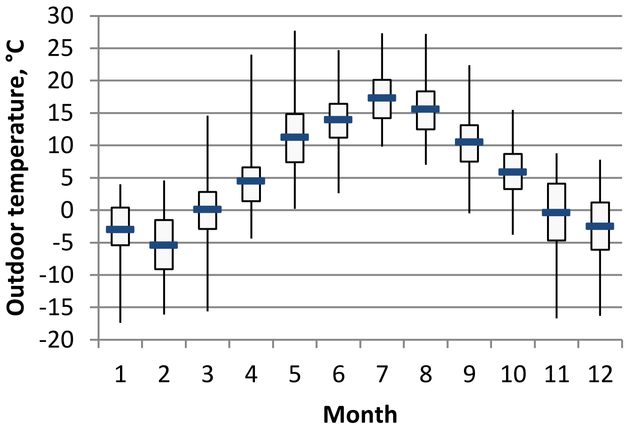


**Figure 2 The minimum, maximum and average temperatures of each month of Estonian test reference year. The average values are indicated with dark markers and the 25th and 75th percentiles are also presented.**

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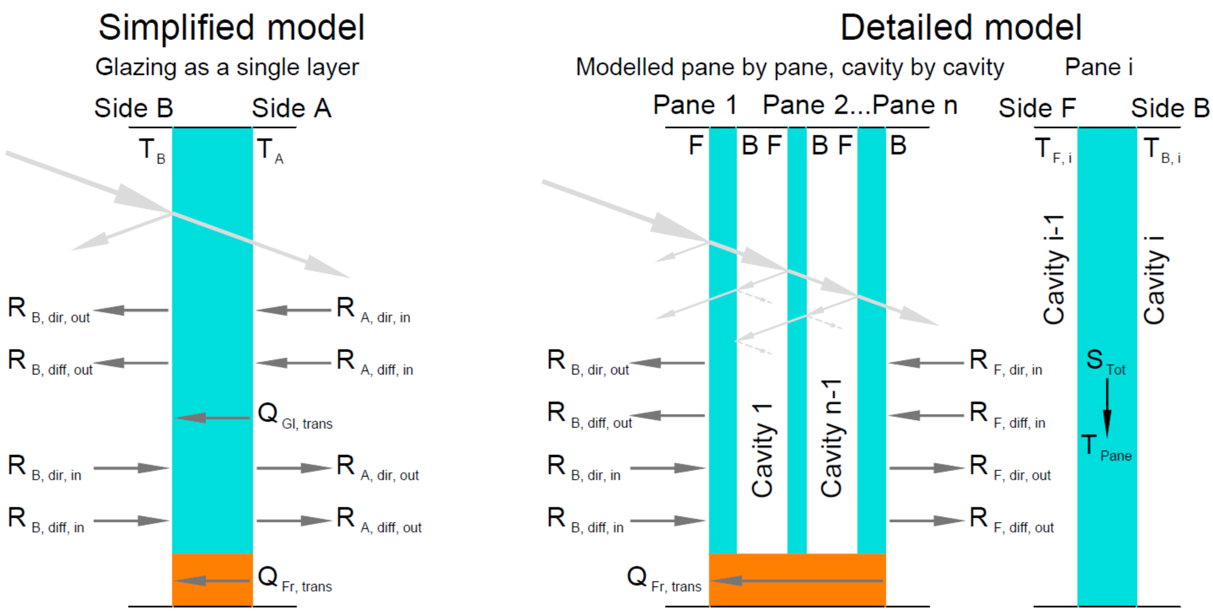


**Figure 3 The calculated variables of simplified and detailed glazing models in IDA-ICE. Code: T – temperature of a surface or pane; R – diffuse/direct radiation in/out of a pane/glazing; Q – heat transmission of glazing/frame from surface to surface; S – total absorption heat flux.**

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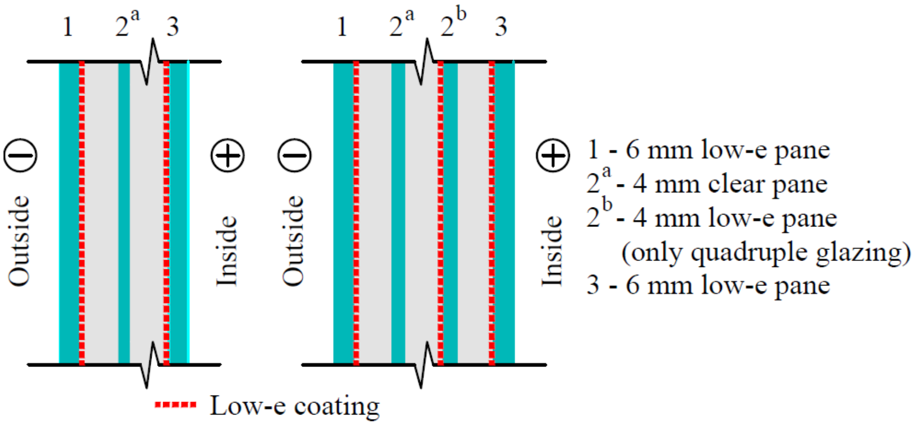


**Figure 3 The construction of triple and quadruple glazing and positioning on low-emissivity layers.**

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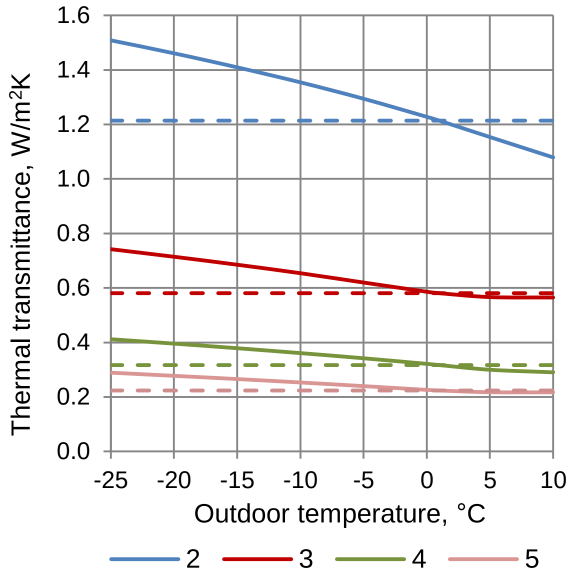


**Figure 4 The glazing U-value depending on the outdoor temperature in static conditions and in case of indoor temperature 21 °C. Declared U-value at reference conditions [17] is marked with dashed lines. The numbers in the legend represent the number of panes in highly transparent glazing.**

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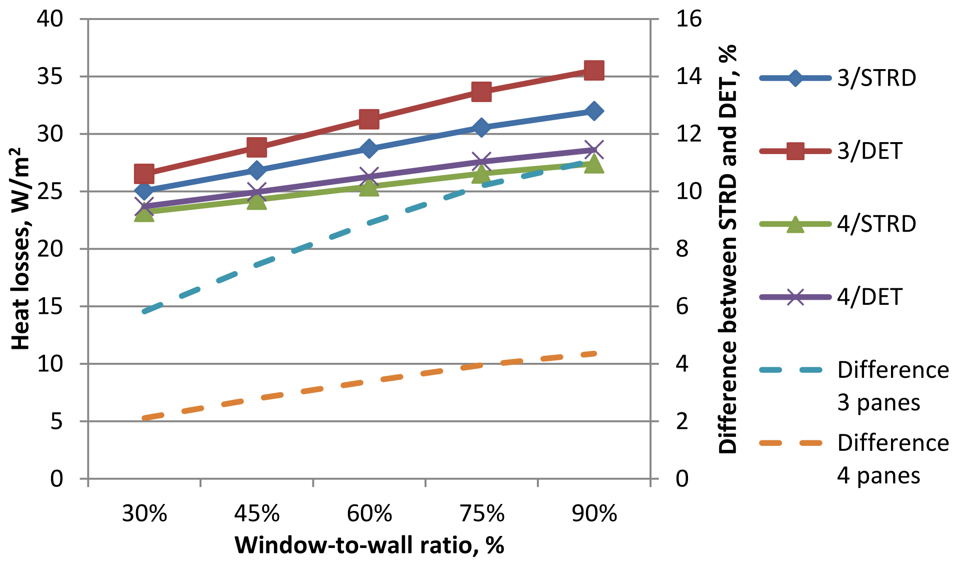


**Figure 5 Heat losses of the building at outside temperature -22 °C with different window-to-wall ratios, glazing models and number of panes. Dashed lines represent the difference between detailed and simplified models.**

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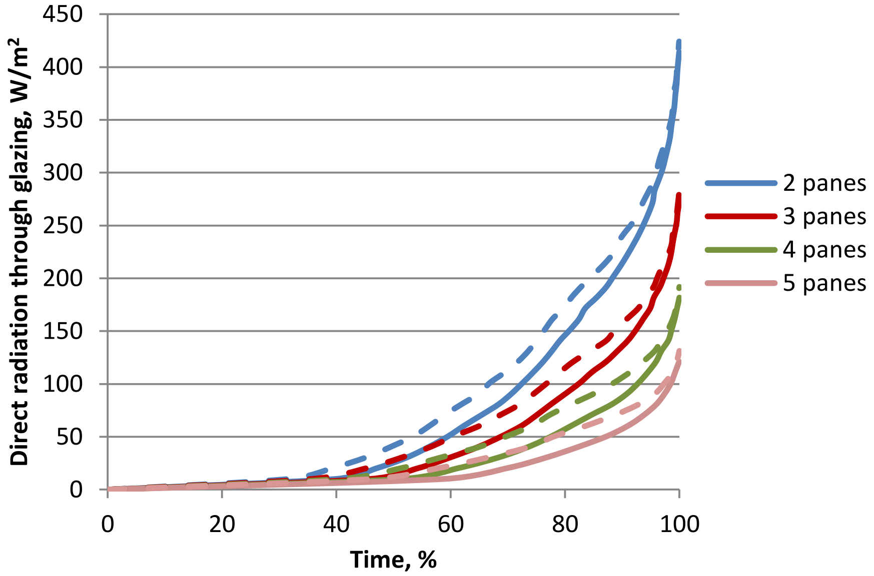


**Figure 6 Direct solar radiation to zone per area of glazing. The continuous and dashed lines represent detailed and simplified window models respectively.**

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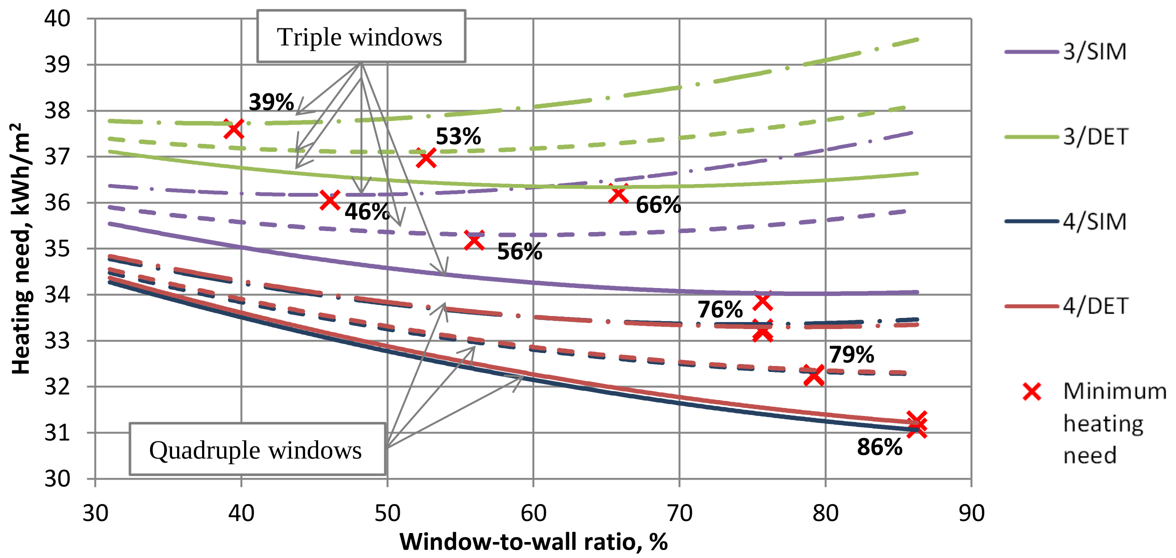


**Figure 7 The heating need and optimal window –to-wall ratio of studied window models with different control strategies and with or without cooling. The figure presents the results when only the South facade window sizes were varied. The continuous lines represent cases with constantly closed windows, dashed lines cases with window opening and dashdot lines cases with mechanical cooling in addition to window opening.**

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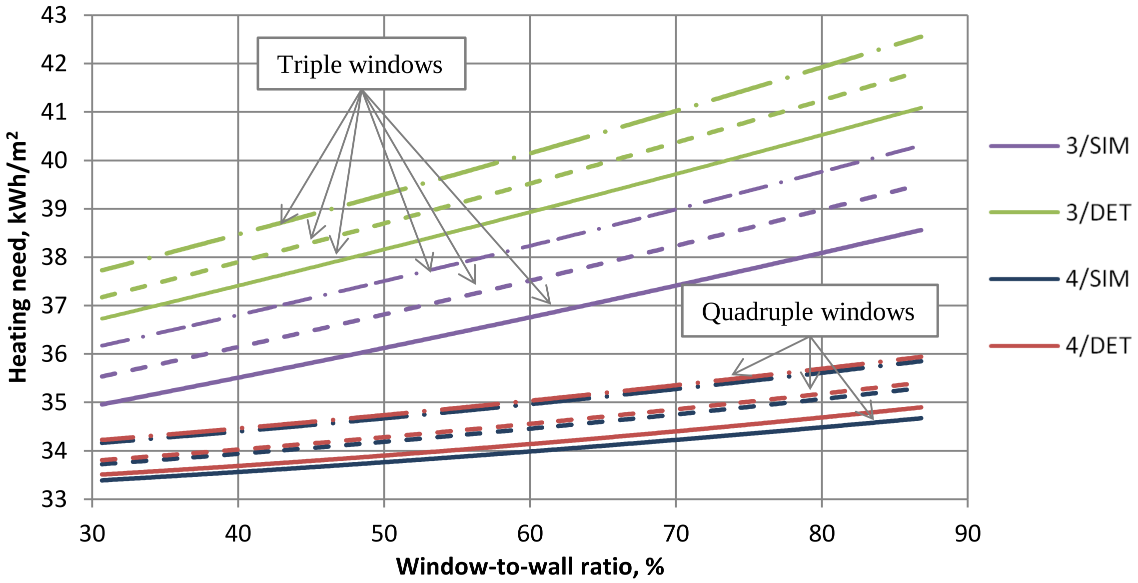


**Figure 8 The heating need and optimal window –to-wall ratio of studied window models with different control strategies and with or without cooling. The figure presents the results when only the West facade window sizes were varied. The continuous lines represent cases with constantly closed windows, dashed lines cases with window opening and dashdot lines cases with mechanical cooling in addition to window opening.**

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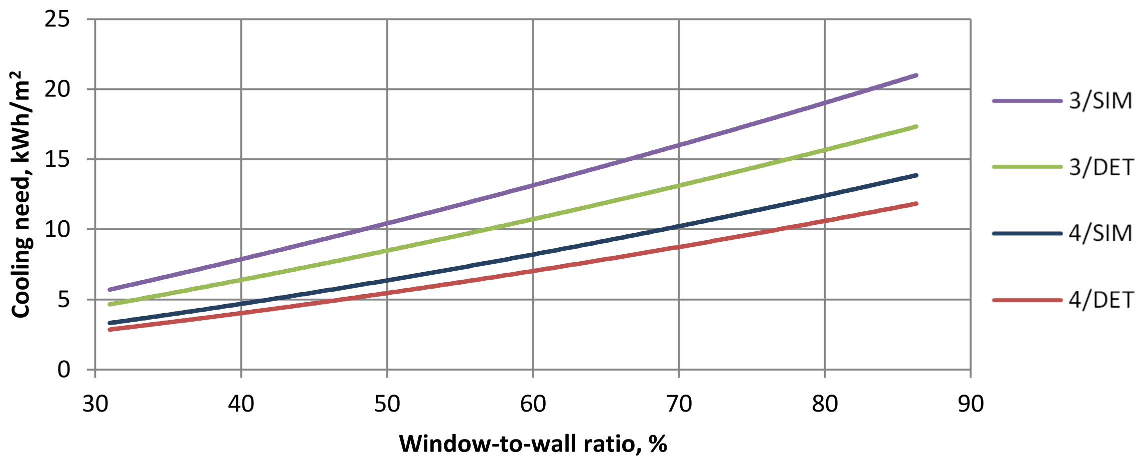


**Figure 9 The cooling need of studied window models with different window-to-wall ratios. The figure presents the results when only the South facade window sizes were varied.**

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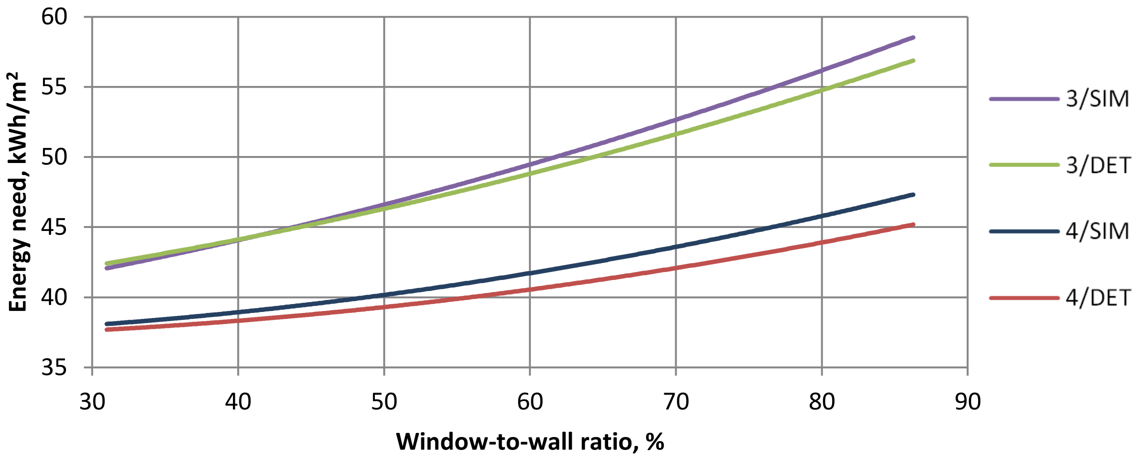


**Figure 10 The sum of heating and cooling needs of studied window models with different window-to-wall ratios. The figure presents the results when only the South facade window sizes were varied.**

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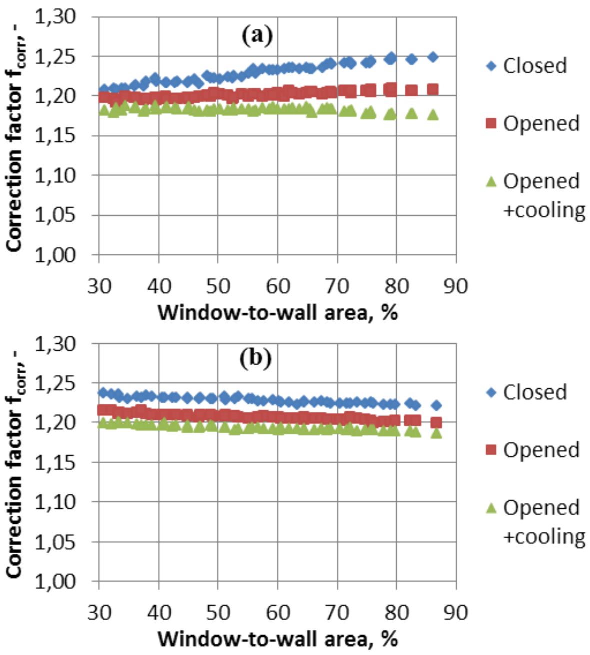


**Figure 11 The predicted correction factors for simplified triple windows to minimize the gap in energy need with detailed window models. (a) and (b) represent cases when only the South or West facade windows were changed respectively.**

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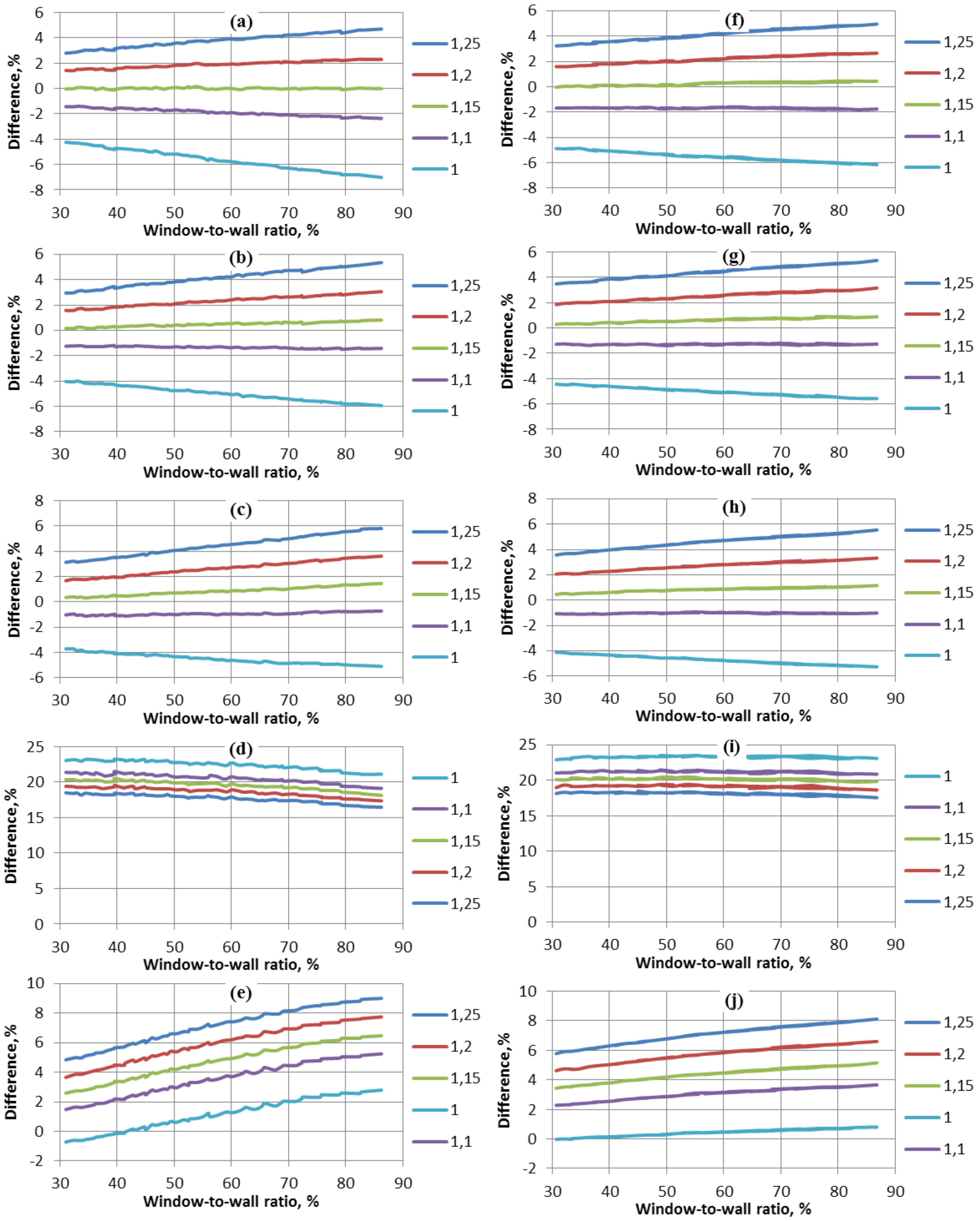


**Figure 12 The differences in energy need of simplified triple window models from detailed window models in case of analyzd correction factors. If difference is over 0, then simplified models result in higher energy need than detailed models. Code: a, f – heating need, closed windows; b, g – heating need, opened windows without cooling; c, h – heating need, opened windows and cooling; d, i – cooling need; e, j – energy need of models with cooling; a, b, c, d, e – window sizes only in the South facade were changed; f, g, h, i, j – window sizes in the West facade were changed.**

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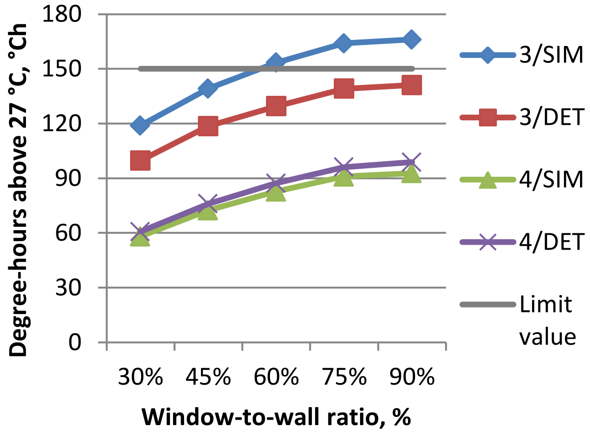


**Figure 13 Degree-hours exceeding 27 °C in the bedroom in the South-West corner of the first floor during the period from June 1st to August 31st. According to Ref. [26] the limit value is 150 °Ch.**

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**Table 1 The description of the initial building envelope.**

| Structure | U-value, W/(m$^2$K) | Area, m$^2$ | Specific heat loss H, W/K | % of total |
|---|---|---|---|---|
| External wall | 0.18 | 151.4 | 26.6 | 27.1 |
| Roof | 0.15 | 75.7 | 11.4 | 11.6 |
| Slab on ground | 0.23 | 72.5 | 16.8 | 17.1 |
| Windows | 0.60 | 41.9 | 25.2 | 25.7 |
| Doors | 1.1 | 2.1 | 2.2 | 2.2 |
| Thermal bridges | - | - | 13.2 | 13.4 |
| Infiltration[a] | - | - | 2.9 | 3.0 |
| Total/weighted average | 0.28 | 343.6 | 98.2 | 100 |

[a] – Constant infiltration of 2.4 l/s (corresponding $q_{50}$=0.6 m$^3$/h per building envelope m$^2$).

**Table 2 Input data of the zones and HVAC systems for energy calculations.**

| | |
|---|---|
| Occupants, W/m$^2$ | 3 |
| Equipment, W/m$^2$ | 3 |
| Lighting, W/m$^2$ | 8 |
| Temperature setpoint for heating, °C | +21 |
| Air flow rate, l/(s·m$^2$) | 0.42 |

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**Table 3 The properties of studied window types.**

| | Triple glazing | Quadruple glazing |
|---|---|---|
| Glazing U-value[a], W/(m2K) | 0.55 | 0.32 |
| Glazing g-value, - | 0.45 | 0.34 |
| Glazing solar transmittance, - | 0.36 | 0.24 |
| Glazing visible transmittance, - | 0.71 | 0.63 |
| Glazing internal emissivity, - | 0.89 | 0.89 |
| Glazing external emissivity, - | 0.89 | 0.89 |
| Gap between panes, mm | 18 | 12 |
| Gas filling | 90% argon | 95% krypton |
| Frame U-value, W/($m^2$K) | 0.8 | 0.8 |
| Frame fraction of window area, % | 20 | 20 |
| Total window U-value, W/($m^2$K) | 0.6 | 0.42 |

[a] – The parameters of simplified windows remained constant during simulations and were given according to calculations of ISO 15099:2003/E at internal and external temperature difference of 20 °C. The energy balance of detailed windows was simulated also according to ISO 15099:2003/E.

**Table 4 Glass pane properties of detailed window models.**

| Pane | Thermal conductivity, W/(mK) | Total shortwave transmittance, - | Total visible transmittance, - | Outside | | | Inside | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Total shortwave reflectance, - | Visible reflectance, - | Longwave emissivity, - | Total shortwave reflectance, - | Visible reflectance, - | Longwave emissivity, - |
| Low-e | 1.0 | 0.62 | 0.88 | 0.23 | 0.06 | 0.89 | 0.27 | 0.05 | 0.03 |
| Clear | 1.0 | 0.85 | 0.90 | 0.08 | 0.08 | 0.89 | 0.08 | 0.08 | 0.89 |